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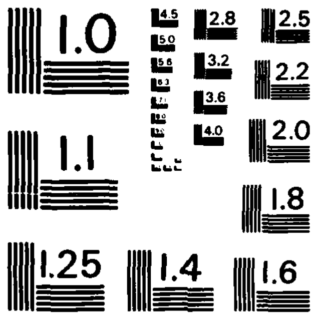

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TESTING OF A FIELD PORTABLE GPS GEODETIC RECEIVER

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ABSTRACT

The Defense Mapping Agency, in cooperation with the United States Geological Survey and the National Oceanic and Atmospheric Administration, is sponsoring the development of a Global Positioning System geodetic receiver. The receiver is capable of observing up to four satellites simultaneously by sampling segments of broadcast signals from different satellites in a time-multiplexing sense using a single dual frequency channel. The receiver system was designed to measure the geodetic coordinates of points to an accuracy of one meter and to provide first-order estimates of baselines of up to several hundred kilometers in length. In addition, the receiver can support positioning and attitude determination of geophysical survey platforms under low dynamic conditions.

Four receiver units have been ~~utilized~~ in extensive laboratory and field tests. Static positioning tests were designed to determine system performance. These tests have provided data for analysis of point and relative positioning over baselines between 30 meters and 100 kilometers in length. Another series of dynamic tests was designed to evaluate system performance in varying dynamic environments. Tests at the Yuma Proving Ground ~~in Arizona~~ used both a jeep and helicopter as platforms, with a laser positioning system for dynamic reference. Tests by the Naval Oceanographic Office in Bay St. Louis, Mississippi, used a 36-foot motor launch as a platform, with a set of trisponders used as the reference system.

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Four receiver units have been utilized in extensive laboratory and field tests. Static positioning tests were designed to determine system performance. These tests have provided data for analysis of point and relative positioning over baselines between 30 meters and 100 kilometers in length. Another series of dynamic tests was designed to evaluate system performance in varying dynamic environments. Tests at the Yuma Proving Ground in Arizona

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1. INTRODUCTION

Soon after conceptual development of the GPS by the Department of Defense, proposals were made by a number of investigators for the application of GPS to geodetic problems. Simulations indicated that multiple channel GPS receivers could achieve geodetic accuracy after several hours on station. This led to the decision to develop GPS receiver systems designed and tailored to meet various geodetic requirements. The Defense Mapping Agency, in cooperation with the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), sponsored the development of a NAVSTAR Global Positioning System (GPS) geodetic receiver to meet geodetic requirements and to support geophysical survey.

This paper will discuss several test applications of this receiver and provide some initial results.

2. THE NAVSTAR GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System is a satellite-based navigation system designed to provide continuous all-weather, worldwide navigation to appropriately equipped users (Payne, 1982). The operational system, scheduled for the late 1980s, will consist of 18 satellites in circular orbits having 55-degree inclination with orbit periods of about 12 hours. This constellation geometry provides the visibility of four to seven satellites anywhere in real-time. Each satellite carries an atomic clock with long-term stability. Navigation signals consisting of spread spectrum, pseudorandom noise (PRN) signals on two coherent L-band frequencies are transmitted continuously.

3. GPS GEODETIC RECEIVER SYSTEM

The receiver system consists of a single RF/IF channel that continuously, in a time-multiplexing sense, tracks four satellites. Each satellite is assigned a software tracker that samples code and carrier information from both L1 (1575.42 MHz) and L2 (1227.6 MHz). The samples are used to update code and carrier software tracking loops which ultimately provide pseudorange and phase observations (Ward, 1982).

Physically the receiver weighs 50 pounds, is battery-operated, and is intended to be a rugged field-portable system. It is composed of antenna/preamplifier, connecting cables, a receiver section, receiver processor, navigation processor, and peripherals. The antenna/preamplifier is a nine-inch high cone sitting on top of a two-inch high preamplifier housing that can be located up to 100 feet from the receiver. The receiver and navigation processor are in the same 15 by 17 by 8-inch housing. A control display unit attached to a six-foot cable is a part of the receiver/navigation processor. Normally, a dual cassette recorder is used. For several applications, however, the data recording will be handled by a different data storage system.

The receiver can be thought of as a software machine since most of the receiver functions are handled by the receiver processor, an SBP 9990 microprocessor, with RAM making up 75 percent of the memory. A second SBP 9990 is employed to perform geodetic solutions in real-time by communicating, through shared memory, with the receiver processor. The system's flexibility, offered by this dual microprocessor RAM memory arrangement, makes the receiver an ideal system for various applications of the Global Positioning System.

4. APPLICATIONS

The geodetic receiver was developed for stationary, absolute and relative positioning applications. The receiver can, however, be used with various low dynamic geophysical survey platforms. The sections that follow will describe some of these applications in more detail.

4.1 Geodetic Positioning

The primary application which led to the development of the GPS geodetic receiver system is geodetic positioning analogous to dynamic point positioning currently performed using the Transit satellite system (Smith, et al., 1976). In this application, either range or integrated Doppler (phase accumulation) observations using both L1 and L2 are obtained from four satellites simultaneously during a site occupation of less than one day. Two frequency observations are used to eliminate first-order ionospheric refraction. The particular satellites used during the occupation period will vary among those available based on a serial optimization of the site (coordinate) estimation. Additional parameters for receiver frequency error and anomalous tropospheric refraction are included in the estimation as required. Precise GPS satellite ephemerides will provide satellite positions necessary in the post mission data processing algorithms. Real-time position estimation using the broadcast GPS navigation message will be performed for on-site quality assurance.

Detailed simulations of geodetic positioning using range and Doppler observations from a single channel receiver for a GPS-type constellation have inferred positional accuracies of a meter after 24 hours of continuous observation (Fell, 1980). Observational noise levels similar to or larger than those obtainable with the geodetic receiver were assumed. Errors in satellite ephemerides, satellite and receiver atomic oscillators, and tropospheric refraction were considered. Since the receiver, in a time-multiplexing sense, tracks four satellites simultaneously, the satellite geometry will be optimized faster than those assumed in simulation. It is thus anticipated that one meter accuracy in each coordinate of position may be obtained in six to twelve hours, or possibly in less time, if elements of the simulation error budget are improved upon in actual applications.

The capability to perform accurate geodetic positioning worldwide using GPS observations will provide for continued support to those geodetic applications currently supported by Transit satellite positioning. These include the accurate positioning of instrumentation, control for national or regional survey networks, the development of satellite-derived regional geoids, control for photogrammetric mapping, and development of datum transformations.

4.2 Static Baseline Determination

A second geodetic application for the GPS geodetic receiver system, the one of highest priority to the National Geodetic Survey of NOAA, is the estimation of precise baselines between fixed points. Accomplishment of first-order accuracy within a few hours of site occupation is the goal of this development.

The approach to this problem is to simultaneously measure the phase of the two reconstructed GPS carrier frequencies from each of four satellites simultaneously at two or more sites separated by up to hundreds of kilometers. Again, observations are made on two coherent frequencies to eliminatefirst-order ionospheric refraction effects. The phase observations may be treated in one of several ways prior to baseline estimation. Such approaches consist of taking single or double differences of phase observations to eliminate particular error sources or model parameters required using phase observations directly.

Simulations of baseline determination using a single channel receiver with double-differenced phase measurements indicate that first-order accuracy can be achieved for 100-kilometer baselines in about six hours (Fell, 1980). The use of simultaneous phase measurements to four satellites will provide such accuracy in approximately two hours. This level of accuracy has already been demonstrated using the Macrometer (Goad and Remondi, 1983) which adopts a different measurement procedure on only one frequency, but uses a similar data processing approach.

The geodetic and geophysical applications of precise baseline determination include survey densification, monitoring of crustal motion, and transferring local control across areas where conventional survey methods are not applicable.

4.3 Dynamic Relative Positioning

Dynamic relative positioning has been proposed as a means whereby scientific survey ships operating in coastal waters may achieve accurate tracks of position with respect to time. Data would be recorded simultaneously on the ship and at one or more fixed sites on land. After the operations are completed, the data sets would be processed to obtain the desired information. An accuracy goal of less than five meters error in a three-dimensional position fix has been proposed.

Biased range data are recorded by each receiver from four satellites. The bias represents the combination of local time error t_i and satellite time error T_j . The observation is therefore:

$$R_{ij} = r_{ij} + t_i + T_j \qquad (1)$$

where i represents the receiver, j represents the satellite, and r_{ij} is the geometric range from site i to satellite j.

In order to eliminate time errors, the biased ranges are differenced twice. The first difference is performed on the observations at each receiver. One of the satellite observations is subtracted from the other three. This eliminates the receiver contribution t_i and other propagation errors that are common to both transmission paths and have a form similar to a bias.

$$R_{ij} - R_{in} = r_{ij} + t_i + T_j - r_{in} - t_i - T_n$$

$$R_{ij} - R_{in} = r_{ij} - r_{in} + T_j - T_n \qquad (2)$$

The second difference is performed between observations of a single satellite recorded by both receivers. This removes satellite timing errors and reduces other errors, such as radial orbit error, that have a similar form:

$$R_{ij} - R_{in} - (R_{mj} - R_{mn}) = r_{ij} - r_{in} + T_j - T_n - (r_{mj} - r_{mn} + T_j - T_n)$$

$$R_{ij} - R_{in} - R_{mj} + R_{mn} = r_{ij} - r_{mj} - (r_{in} - r_{mn}) \qquad (3)$$

The resulting quantity contains multiple differences of ranges between satellites j and n and receivers i and m. It is of no particular advantage to locate the fixed sites near dynamic sites. All that is required is that they observe the same satellites over a substantial period of time.

This doubly differenced data can then be used to solve for the dynamic receiver position relative to the stationary sites. It is expected that sufficient data will be accumulated during planned field test to evaluate various techniques and geometric arrangements of receivers. The intent is to have one or more fixed receivers and one to several dynamic receivers. The data collected will be both pseudorange and accumulated Doppler phases along with the broadcast ephemeris and other support data. The strength of these solutions will be compared to solutions calculated using standard differencing procedures.

4.4 Attitude Determination

Prior to the development of the NAVSTAR Global Positioning System, only inertial measurement systems had the potential to provide both position and platform orientation, 6 degree-of-freedom information, as a stand-alone system (Johnson, et al., 1981-82). Now, GPS receivers have been successfully used to determine antenna position (Henderson and Strada, 1980; Lachapelle, et al., 1982; and O'Toole and Carr, 1982). Also, a number of proposals have been made to use phase measurements from multiple GPS satellite tracking receivers to determine platform orientation (Johnson, et al., 1981-82; Ellis and Greswell, 1979; and Griffin and Coulbourn, in press). These proposals adopt interferometric procedures using the phase of the satellite-transmitted carrier signals measured at the same instant at two or more antennas.

4.4.1 Fixed Antennas

Three points, not in a straight line, define the orientation of a plane with respect to a given coordinate system. If a vehicle is attached to this plane, then the vehicle orientation is also determined. The Global Positioning System of satellites defines a coordinate system which can be related to the fixed earth. The GPS satellites also provide coded signals which can be received, decoded, and processed with a suitable algorithm to establish the location of the receiver antenna with respect to this coordinate system at a specific time. Repeated processing of the received GPS signals will produce a three-dimensional track of the vehicle's position with respect to time. This information can then be used to navigate the vehicle. In a similar fashion, the three-axis orientation of a vehicle can be computed if signals are available simultaneously from three or more antennas.

In order to do three-axis orientation, the three antenna positions must be known relative to each other in the vehicle reference frame. Then, comparison of the phase of the GPS signals received at the several antennas allows one to orient the plane containing the antennas with respect to the GPS coordinate system.

Simultaneous three-dimensional navigation and three-axis orientation are possible if a suitable receiver and reduction algorithm are mated. The time-multiplexed receiver goes a long way towards meeting the receiver requirement of tracking four satellites (for instantaneous navigation) simultaneously from three antennas (for instantaneous orientation). The system would use software to multiplex the received signals among the several software tracking loops. These loops operate independently on an assigned satellite signal and frequency.

The receiver has a fundamental clocking interval of 20ms(T). All receiver operations are some integer fraction or multiple of T. Typically, the receiver dwells for T/2 on each satellite and T/4 on each frequency of a particular satellite. Thus, it has completed an observation cycle appropriate for the navigation function using a single antenna (two frequencies and four satellites) after 2T. Collecting data to solve the orientation problem requires that an RF switch be inserted between the antennas and the receiver. This switch would be activated in synchronization with the receiver clocking interval T. Then when the switch is operated, the next antenna would be selected to feed signals to its dedicated software tracking loops. In the time between updates of a particular tracking loop, it would propagate using the most recent data. Thus, it might be possible to keep several auxiliary sets of tracking loops (one set per antenna) running in the navigation processor, each set being updated by the receiver processor software. Update intervals of these auxiliary trackers would be at intervals of 2NT, where N is the number of antennas being used. The receiver would then provide the data from all of its tracking loops to an external computer. This computer would contain the navigation and orientation algorithms and display the continuously updated solution.

Navigation accuracies depend upon the precision of the pseudorange measurement, the errors in the satellite ephermeris, and the geometric strength of solution provided by the observed satellites. Receiver pseudorange accuracies using P code tracking are quoted as being less than 1.5 meters (Johnson, et al., 1981-82). Therefore, expected three-dimensional positioning should be as good as any conventional code tracking receiver.

Orientation accuracies are proportional to the accuracy of the phase difference measurement (Δl_i), and inversely proportional to the distance between the antennas (b_i) multiplied by the sine of the angle between the line connecting the antennas and the satellite vector:

$$\Delta\Theta ij = \frac{\Delta l_i}{b_i \sin \Theta_{ij}} \qquad (4)$$

The subscripts in this equation indicate the particular baseline (i) and satellite (j).

Receiver phase measurement accuracies are expected to be about 0.005 meter. If an optimal four satellites are always contributing data, then the resulting angular precision will not be seriously perturbed should the position of one satellite cause the sin Θ_{ij} to approach zero.

Simulations have shown that equation (4) can be used to estimate the angular accuracies that result for a given phase measurement error and baseline length. For example, the standard deviation of the angular estimate, given a 2-meter baseline and a measurement error of 0.005 meter, can approach 3 milliradian (Hermann, in press).

4.4.2 Rotating Antenna

Instead of phase measurements, an alternate procedure uses change-in-phase measurements. This removes the requirement that the phase measurements be coherent. Also, instead of using three fixed antennas on a platform, the procedure uses one antenna rotated in the plane of the platform. Therefore, no additional signal channels are required of the reciever in order to determine both real-time positioning and orientation for low dynamic vehicles.

This platform orientation procedure takes advantage of two physical characteristics. First, the GPS receiver is designed to track four satellites even when the antenna is attached to a high dynamic vehicle, such as a fast airplane or missile. The proposed procedure is to be used on low dynamic vehicles, such as boats, helicopters, or slow-flying aircraft which support geophysical surveys. Therefore, the antenna will be able to have some additional motion and the receiver will still be able to track four satellites.

Secondly, movement of the antenna away from its location and then back does not change the phase measurements from those which would have taken place if the antenna had not moved between measurement times. Here, it may be necessary to deterministically compensate for antenna spin. This is a result of the Doppler effect and assumes that the receiver is tracking satellites during the antenna motion.

The proposed procedure is to periodically change the position of the electrical center of the antenna. The position change is done slowly enough not to lose track on the satellites, but faster than the dynamics of the vehicle. The periodic changes in antenna position imply periodic changes to known positions on the vehicle, which are synchronized in time with receiver measurements.

The procedure is not restricted to a specific type of periodic motion. One of the simplest applications would be periodic circular motion in the plane of the platform. This would be accomplished by placing an antenna at the end of a rotating arm, or within a rotating disk. The antenna may require a coupler for connection to the receiver cable. The accuracy of such a device would depend on a number of factors. Most important are the radius of the circular motion, the change-in-phase measurement accuracy, the vehicle dynamics, the rotational rate, rotational positioning accuracy and the clock accuracy. Many other types of configurations are possible, and the change in position of the antenna's electrical center could also be accomplished electronically rather than mechanically.

The orientation estimation is, of course, made at discrete times. In a dynamic situation, the vehicle and the antenna move between measurements. Consequently, an interpolation procedure is necessary to estimate the measured values at the appropriate times.

A static demonstration of GPS attitude determining capabilities has been performed. Here, available data (Evans, et al., 1981) from a Stanford Telecommunications, Inc. (STI) geodetic GPS receiver were used. The antenna was periodically moved to three locations of a platform. The position changes were every 15 minutes and done within a 60-second change-in-phase measurement interval. Since the receiver tracks only one satellite at a time, data from repeated position changes were used to emulate tracking multiple satellites during the tracking interval.

The change-in-phase measurements are used to obtain observed values of change in range. This is done by integrating the received frequency $f_r(t)$, subtracted from a precise ground station frequency f_g over a time interval (t_{i-1}, t_i). The received frequency is the sum of the transmitted frequency f_t and the Doppler effect. Therefore, the change in phase, in cycles, is

$$\Delta\phi = \int_{t_{i-1}}^{t_i} \left(f_g - f_r(t)\right) dt \tag{5}$$

$$\Delta\phi = \int_{t_{i-1}}^{t_i} \left(f_g - f_r + f_r \frac{\dot{R}(t)}{c}\right) dt \tag{6}$$

$$\Delta\phi = \left(f_g - f_r\right)\left(t_i - t_{i-1}\right) + \frac{1}{c} f_r \left(R\left(t_i\right) - R\left(t_{i-1}\right)\right) \tag{7}$$

where c is the speed of light and R(t) is the range at time t to the satellite. The measured change in phase is used to determine the observed change in range using equation (7). Using the change-in-range values from the two-frequency GPS channels, a first-order ionospheric correction is made.

Next, the calculated ranges from the assumed positions are fit to the data to determine biased ranges and improvements to six orbit elements and tropospheric refraction corrections. The difference in the residuals of these fits at times before and after the antenna moves represents the observed change in range due to the position changes. The details of this method have been presented previously (Evans, et al., 1981).

Thus, a procedure may be available to determine platform orientation using the Global Positioning System and a multiple satellite tracking receiver using change-in-phase measurements from an antenna whose electrical center is periodically moved within a plane. In order to demonstrate the procedure further, available change-in-phase measurements from an antenna moving in a stationary plane are required.

5. RECEIVER TEST PROGRAM

In 1982, the Applied Research Laboratories of the University of Texas at Austin published a preliminary test plan for the GPS Geodetic Receiver System. The basic goals of the tests were to determine the usability of the receiv system, its reliability, and the accuracy of data obtained under vary environmental conditions and satellite tracking geometries.

Some specific objectives of the tests are enumerated below:

1. Determine antenna and oscillator contributions to the measurement error budget.

2. Evaluate positioning accuracy, both point and relative, using baselines of variable extent.

3. Maintain records of setup time, operating time, and maintainability.

4. Initiate statistical database for reliability and maintainability.

5. Determine environmental effects on system availability.

6. Evaluate effects of atmospheric moisture on data precision and accuracy.

7. Establish vulnerability of the receiving system to radio frequency interference.

8. Evaluate transportability, time required to unpack and set up, power consumption, time required to repack and relocate, suitability of transportation container.

9. Evaluate field suitability of the control display unit, tape recorder assembly, and antenna/preamplifier assembly.

10. Evaluate field maintainability, suitability of spares kit, and field maintenance instruction manual.

11. Establish system accuracy in moving ground vehicles and aircraft at the Yuma test site.

12. Determine areas of GEOSTAR improvement, considering human factors in its deployment, operation, and maintenance.

The program was subsequently expanded to include additional navigation and initiate platform orientation testing.

This test plan encompasses seven major operational phases:

A. Collocation Tests at ARL:UT Sites

1. Antenna/Preamplifier Evaluation

Purpose: Isolate error contributions to receiver system error budget from antenna/preamplifier, and from reference oscillators.

2. Relative Positioning Tests Using Three Receivers in Austin

Purpose: Five different objectives will be addressed: maintaining reliability data; establishing average field setup times; evaluating receiver field suitability; determining environmental effects; and establishing relative positioning accuracy over short baselines.

B. Multiposition Relative Tests Over Short (Less than 1 km) Baselines

Purpose: These tests will establish point positioning and relative position accuracies over baselines separated by 500 to 800 m. Additionally, the reliability database and field operating experience will be extended by data recorded during these tests.

C. Relative Tests over Medium (Less than 300 km) Baselines

1. 10-20 km Baseline Tests

Purpose: Evaluate point positioning accuracy at first-order survey benchmarks (in the NAD-27 reference system), determine relative positioning accuracy for points separated by 10-20 km distances, obtain statistical data for environmental effects analysis, reliability, field maintenance, and operational suitability, and evaluate effects of a radar transmitter on the receiver.

2. 100-200 km Baseline Tests

Purpose: Three GEOSTAR receivers will be positioned at first-order survey points separated by distances of 100-200 km. Similar tests will again be repeated (see section C.1).

D. Geodetic Positioning Over Extended Baselines

1. Extended Baselines on the Transcontinental Traverse (TCT)

Purpose: The purposes are twofold: i) to add to the statistical database for reliability, operational setup time (field suitability), and maintainability; ii) to evaluate the effects of tropospheric path length variations on relative position accuracy at receiver separations of 1000 km.

2. VLBI Relative Position Tests

Purpose: Radio astronomy measurements have been made over extended interferometric baselines for a number of years, using radio telescopes at various sites throughout the country. Three of these sites will be simultaneously occupied following the tests at Yuma (see below). Coordination will be effected with the University of California at Berkeley for access to two sites in California, and with The University of Texas for setup at the Fort Davis observatory. An exact timetable for these tests has not been established, since they depend on resource availability. Both point positioning and relative triangulation tests will be performed.

E. Yuma (Arizona) Experiments

1. Point Positioning Tests

Purpose: These tests will evaluate the point positioning accuracy and satellite acquisition performance of the receiver system.

2. Dynamic Navigation Tests

Purpose: The purpose of these tests is to demonstrate the navigational accuracy of the time-multiplex receiver over a range of platform dynamics. Measured positions over time will be compared with independently observed positions to define the accuracy of the receiver at different platform velocities. Overall suitability for this application (navigation) will be established.

F. Hydrographic Survey Test

Purpose: These tests will establish the performance of the GPS Receiver System in positioning a hydrographic survey ship both by direct stand-alone positioning and by dynamic relative positioning with respect to known terrestrial surveying points.

G. Ship Altitude Tests

Purpose: These tests will determine the system s ability to determine the altitude of a ship platform at sea.

Initial tests of the concepts will begin in 1984 with support and cooperation from the Eastern Space and Missile Test Center, Patrick AFB, Florida. Three GPS geodetic receivers, paired with three antennas, will operate in the conventional navigation mode aboard the USNS Redstone, a

scientific survey ship. The three receivers will be synchronized to a single frequency standard and will track the same satellites so that simultaneous phase data are available. This is crucial for a successful test. The broadcast ephemeris, receiver diagnostics, pseudoranges, and phase data will be recorded on tape for postprocessing. Comparison data will be provided by the ship s inertial navigation system. Should the results of the processing show promise, work will begin toward implem ıting the real-time system.

6. PRELIMINARY RESULTS

Data acquired during all field testing operations have been under analysis to assess performance characteristics of the receiver system against design specifications and to derive accuracy measurements for these preliminary positioning results. Preliminary results are presented for two of the test activities.

6.1. Baseline Results at Intercomparison Sites

Observational data were gathered in southern California at nine sites (Table 1) by both the GPS Geodetic Receiver System, Macrometers, and SERIES equipment developed by the Jet Propulsion Laboratory for NASA. Site locations had previously been surveyed to first-order by the National Geodetic Survey. Observations were acquired at sites on difficult days in 1984, day 19 through day 33, with at least two sites tracking the same GPS satellites simultaneously.

The technique used to generate position solutions is the double difference approach, discussed above, using biased range from integrated phase extracted at one or five minute intervals. A prior uncertainty of 1 cm was assigned to each observation and the orbit was scaled to a GM of 398600.5. General relativity correction was applied, but not special relativity. The model for tropospheric refraction was the Hopfield model. The parameters assigned were: 1) a refraction scale parameter for each station to satellite combination with an uncertainty of one percent; 2) a clock epoch and rate ambiguity for station 1, assigned with small standard errors. For each "event" (observations of up to four satellites for up to two stations within a one minute interval), a clock epoch and rate parameter were estimated for each satellite and the second station. Large standard errors were assigned to clock epochs, and standard errors of at least 100 ns/day were assigned to clock rates; 3) an ambiguity parameter for each segment of phase lock on each satellite for each station was assigned with a large standard error; and, 4) for all data of the day, the rectangular coordinates of each station were determined with the components for station 1 assigned a 10 meter uncertainty. Six orbit constants for each satellite were included with coefficients of periodic (orbit period) variations assigned an uncertainty of 5, 10, and 15 meters (radial, tangential and out-of-plane), respectively.

Table 2 presents the baseline solutions using doubly-differenced integrated phase measurements treated as biased ranges. The table indicates whether ionospheric refraction corrections were applied to the data, the baseline component solutions, and the formal uncertainty from the least squares adjustment.

Since first-order survey coordinates were not immediately available from NGS, Table 3 was assembled from data in Table 2 to demonstrate the consistency of the results when baselines were re-observed on subsequent days. For instance, for stations 85035 and 85036, the baseline was estimated on days 26, 28, and 29. The solution for the baseline components is listed under day 26 in the table. Under days 28 and 29 are the changes to the day 26 estimated baseline using data from each of those days. For these stations the baseline components show a repeatability of 3.3 parts per million or better. Results for the other repeated baselines are provided in Table 3 and demonstrate similar levels of precision.

6.2. Hydrographic Survey

Eleven days of data were acquired by the Naval Oceanographic Office aboard a survey launch during the hydrographic survey test. Nine days of data have been processed at this point in time. Of this data, three days included four-satellite, two-frequency data. These data produced positioning solutions varying between 17 and 19 meters as a 90 percent CEP when compared to the test control derived from a Del Norte radio positioning system whose accuracy varies between 2 to 3 meters. Thus, at this point in the analysis, the results are very encouraging.

7. CONCLUSION

An exhaustive test program has been executed to assess accuracies in the applications noted above and to determine the receiver systems usability, reliability, and susceptivity to operational environmental changes. Preliminary positioning results for baselines indicate that the receiver system will meet design specifications. Initial results indicate acceptable performance in the navigation role. Final test program results will be published as a separate report at the end of the data reduction phase.

BASELINE INTERCOMPARISON SITES

Station Number	Station Name
85031	Moblas 7115 Rm 1
85032	Harvard Rm 4
85033	BP Aries 3 1977
85034	LA Co Mark
85035	Mojave NCMN 2 1965
85036	Barstow 2 No 1 1965
85037	Lucerne S.B. Rm 3
85038	Mesquite 1939 Rm 2
85039	Point 1965

TABLE 1

TABLE 2: BASELINE RESULTS USING DOUBLY-DIFFERENCED INTEGRATED PHASE OBSERVATIONS TREATED AS BIASED RANGE

DAY	23	26	28	28	28	29	29	29	30
STATION 1	85034	85035	85031	85031	85035	85031	85031	85035	85035
STATION 2	85033	85036	85035	85036	85036	85035	85036	85036	85999
DATA INTERVAL (min)	1	1	1	1	1	5	5	5	5
IONO CORRECTED?	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes
$\Delta\lambda° \times 10^5$	-11134.414	-4805.367	-9893.001	-14698.247	-4805.243	-9892.967	-14698.335	4805.393	9892.869
$\Delta\phi° \times 10^5$	302636.733	-23943.137	8219.010	-15724.159	-23943.098	8219.088	15724.240	23943.191	-8219.048
ΔH (m)	738.805	446.120	-143.760	302.435	446.216	-143.817	302.456	446.224	143.816
ΔX (m)	83563.858	-11001.605	-5598.880	-16600.415	-11001.545	-5598.828	-16600.474	-11001.652	5598.777
ΔY (m)	176958.574	-12003.444	8869.765	-3133.781	-12003.534	8869.798	-3133.782	-12003.562	-8869.783
ΔZ (m)	273057.214	-21450.102	7361.148	-14688.874	-21450.011	7361.158	-14088.878	-21450.013	-7361.173
D (m)	335942.700	26929.999	12814.316	21997.517	26929.943	12814.322	21997.564	26930.000	12814.297
$\sigma\Delta\lambda$ (m)	.234	.110	.110	.033	.045	.054	.061	.065	.141
$\sigma\Delta\phi$ (m)	.096	.060	.033	.011	.104	.013	.016	.017	.055
$\sigma\Delta h$ (m)	.170	.113	.047	.023	.030	.038	.043	.045	.130
$\sigma\Delta x$ (m)	.23	.11	.11	.03	.10	.06	.06	.07	.15
$\sigma\Delta y$ (m)	.12	.08	.05	.02	.04	.03	.03	.03	.09
$\sigma\Delta z$ (m)	.15	.10	.04	.02	.04	.03	.03	.03	.11

TABLE 2: (Continued)

DAY	31	32	32	32	33	33	33	33	19
STATION 1	85039	85031	85031	85037	85038	85038	85039	85039	85032
STATION 2	85031	85039	85037	85039	85039	85037	85037	85037	85033
DATA INTERVAL (min)	1	5	5	5	5	1	1	5	1
IONO CORRECTED?	Yes	No	No	No	Yes		Yes	Yes	No
$\Delta\lambda^\circ \times 10^5$	27568.566	-27568.472	-8947.080	-18621.682	-95438.485	-76816.682	18621.755	18621.762	-1433659.173
$\Delta\phi^\circ \times 10^5$	79428.888	-79429.079	-80855.855	1426.711	26050.933	24624.216	1426.794	1426.885	659601.604
ΔH (m)	152.980	-152.943	-156.211	3.252	276.839	273.787	-3.057	-3.142	-401.663
ΔX (m)	45233.038	-45232.946	-30384.781	-14848.595	-71360.596	-56512.085	14848.467	14848.479	-1085447.751
ΔY (m)	33367.534	-33367.577	-41926.589	8559.089	53688.226	45129.058	-8559.193	-8559.185	853793.189
ΔZ (m)	72410.210	-72410.121	-73717.369	1306.972	24024.718	22717.865	-1306.927	-1307.058	606596.687
D (m)	91666.017	91665.916	90085.095	17188.570	92476.739	75804.677	17188.500	17188.524	1508349.817
$\sigma\Delta\lambda$ (m)	.331	.191	.292	.071	.109	.158	.158	.432	.937
$\sigma\Delta\phi$ (m)	.307	.112	.206	.218	.044	.052	.087	.288	.425
$\sigma\Delta h$ (m)	.270	.268	.202	.177	.077	.100	.143	.466	.633
$\sigma\Delta x$ (m)	.33	.22	.31	.23	.11	.16	.16	.44	.95
$\sigma\Delta y$ (m)	.21	.19	.15	.06	.06	.08	.11	.33	.56
$\sigma\Delta z$ (m)	.36	.20	.22	.17	.06	.08	.13	.42	.48

TABLE 3:

REPEATABILITY OF BASELINE SOLUTIONS

STATIONS	85035/85036			85031/85035		
DAY	26	28	29	28	29	30
$\Delta\lambda$ (deg)	-.04805			-.09893		
$\Delta\phi$ (deg)	.23943			.08219		
Δh (m)	446			-144		
D (m)	26930			12814		
$\Delta\Delta x$ (cm)		5.0	-4.7		5.2	7.1
$\Delta\Delta y$ (cm)		-8.0	11.8		3.3	2.8
$\Delta\Delta z$ (cm)		0.9	8.9		1.0	1.4
ΔD (cm)		-5.6	0.1		0.6	-0.4
$\sigma\Delta\lambda$ (cm)	11.0	4.5	6.5	11.0	5.4	19.0
$\sigma\Delta\phi$ (cm)	6.0	10.4	1.7	3.3	1.3	6.0
$\sigma\Delta h$ (cm)	11.3	3.0	4.5	4.7	3.8	13.5
DATA INTERVAL (sec)	60		300	60	300	300
IONO CORRECTED?	Yes		Yes	No	Yes	No

TABLE 3:
(Continued)

STATIONS	85031/85036		85039/85031		85037/85039	
DAY	28	29	31	32	32	33
$\Delta\lambda$ (deg)	-.14698		.27569		-.18622	
$\Delta\phi$ (deg)	-.15724		.79429		.01427	
Δh (m)	302		153		3	
D (m)	21997		91666		17189	
$\Delta\Delta x$ (cm)		-5.9		-9.3		+12.8
$\Delta\Delta y$ (cm)		-0.1		4.3		10.4
$\Delta\Delta z$ (cm)		-0.4		-8.9		-4.5
ΔD (cm)		4.7		-10.1		-6.2
$\sigma\Delta\lambda$ (cm)	3.3	6.1	33.1	19.1	7.1	15.8
$\sigma\Delta\phi$ (cm)	1.1	1.6	30.7	11.2	21.8	8.7
$\sigma\Delta h$ (cm)	2.3	4.3	27.0	26.8	17.7	14.3
DATA INTERVAL (sec)	60	300	60	300	300	60
IONO CORRECTED?	No	Yes	Yes	No	No	Yes

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